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RESEARCH MEMORANDUM

EFFECTS OF FUEL TEMPERATURE AND FUEL DISTRIBUTION ON THE COMBUSTION EFFICIENCY OF A 16-INCH RAM-JET ENGINE AT A SIMULATED FLIGHT MACH NUMBER OF 2.9

By E. E. Dangle, A. J. Cervenka, and D. W. Bahr

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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EFFECTS OF FUEL TEMPERATURE AND FUEL DISTRIBUTION ON THE COMBUSTION EFFICIENCY OF A 16-INCH RAM-JET ENGINE AT A SIMULATED FLIGHT MACH NUMBER OF 2.9

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SUMMARY

This report presents the effect of preinjection-fuel temperature upon vaporization rates and combustion efficiency of a 16-inch ram-jet engine for two fuels, MIL-F-5624A grade JP-4 and 62-octane gasoline. The effect of controlled circumferential fuel distribution as well as controlled radial distribution upon combustion efficiency is also presented.

In a ram-jet engine, operating at conditions simulating a flight Mach number of 2.9, combustion efficiency was insensitive to fuel preheating and variations in longitudinal location of the fuel injector. Fuel-air surveys indicated that for a fuel temperature of 100° F at the injector, 58 percent of the fuel was vaporized within 6 inches of the point of injection.

The use of individual fuel control sleeves extending from each fuel injector to the flame holder resulted in an almost constant combustion efficiency of approximately 93 percent over the fuel-air ratio range of 0.0475 to 0.0175.

INTRODUCTION

This experimental investigation is part of a ram-jet-combustor design program being conducted at the NACA Lewis laboratory. The objective of this program is the attainment of combustor designs and design criteria which will permit efficient and stable ram-jet combustion over wide ranges of fuel-air ratios and combustor-inlet conditions. This report illustrates the influence of various parameters in the fuel preparation zone upon combustor efficiency. The effect of fuel volatility, fuel preheating, and fuel-injector location upon the combustion efficiency of a ram-jet engine is presented in this report along with the effect of controlled circumferential fuel penetration as well as controlled radial fuel penetration. An indication of the vaporization rates of fuel sprays in an actual ram-jet combustor is also presented. The research was conducted in a 16-inch-diameter ram-jet combustor at inlet

conditions corresponding to a flight Mach number of 2.9, an altitude of 67,000 feet, and a diffuser pressure recovery of 70 percent.

The vaporization rates of single liquid droplets have been studied over wide ranges of experimental conditions (references 1 and 2). Several theoretical, as well as a few experimental, treatments on the rate of vaporization of fuel sprays are reported in references 3 and 4. A theoretical analysis presented in reference 4 indicates the magnitude of fuel-spray vaporization rates under conditions approximating actual ram-jet-combustor-inlet conditions. An indication of the increase in the evaporation rate of a preheated fuel spray as compared with a spray of nonpreheated fuel is reported in reference 5. However, experimental data concerning the evaporation rates of fuel sprays in an actual ram-jet engine were not available. 2713

The condition of the fuel injected into combustors has been found to influence the combustion efficiency. A 10-percent increase in the combustion efficiency of a ram-jet engine has been obtained by fuel preheating (reference 6). These latter efficiency increases, however, were attained with a 20° F inlet-air temperature to the combustor. The effect of fuel preheating in ram-jet engines operating at conditions corresponding to high flight Mach numbers and, thus, with high combustor-inlet-air temperatures had not been previously determined.

APPARATUS

Installation of the test unit is shown in figure 1. The 16-inch ram-jet engine received its air supply from the laboratory combustion-air system and then exhausted through a muffler to the atmosphere. Air flow to the ram-jet engine was controlled by a butterfly valve upstream of the test unit and was metered through an orifice system located in the supply line. The inlet-air temperature to the ram-jet engine was maintained at approximately 600° F; heating of the air was accomplished by means of a gas-fired heat exchanger with no contamination.

The engine-outlet temperatures were obtained by a heat balance. The calorimeter consisted of a multiple water-spray ring located 6 inches downstream of the engine exhaust nozzle, a 24-inch-diameter insulated pipe 22 feet long, and a thermocouple station 20 feet downstream of the water sprays. The resulting gas and steam temperatures at the outlet of the calorimeter were measured by 16 thermocouples located in equal areas across the 24-inch-diameter duct.

Ram-jet engine. - The 16-inch ram-jet engine (fig. 2) used in this investigation was composed of a subsonic annular diffuser, a water-cooled combustion chamber 16 inches in diameter, and a water-cooled fixed-area converging exhaust nozzle.

The over-all length of the engine from the inlet of the subsonic portion of the diffuser to the nozzle outlet was 175 inches, of which the combustion-chamber and nozzle length was 90 inches. The diffuser centerbody extended from the engine-inlet lip and terminated at the combustion-chamber inlet with a pilot burner on the downstream end. The centerbody was held in place by supporting struts.

Pilot system. - A vortex pilot was housed in the downstream end of
2713 the centerbody. The pilot combustion chamber consisted of a truncated cone 10.3 inches long that tapered in diameter from $7\frac{1}{4}$ inches at the upstream end to 6 inches at the exit. The pilot fuel was 62-octane gasoline and the amount burned never exceeded more than 5 percent of the total engine fuel flow. A single fuel nozzle rated at 30.0 gallons per hour at a pressure differential of 100 pounds per square inch was used. Air was scooped from the main centerbody supports and ducted into the pilot through elbows which imparted a vortex action to the air. The fuel was ignited with a commercial jet-engine spark plug.

Fuel. - The properties of the two fuels, MIL-F-5624A grade JP-4 and 62-octane gasoline, used as both primary and pilot fuels, are given in table I.

Fuel heater. - The primary engine fuel was heated from room temperature to 500° F by means of a 180-kilowatt electrical resistance-type heater. Three Inconel heater tubes, each 55 feet long, operating in single phase with a 3-phase 208-volt input constituted the fuel heat exchanger. The heat-exchanger tubes, themselves, provided the electrical resistance. The three tubes were electrically connected in a delta circuit and electrically insulated with Teflon gaskets.

Fuel-injector system. - The fuel injectors were located $17\frac{1}{8}$, $10\frac{5}{8}$, and $4\frac{1}{8}$ inches upstream of the flame holders. Six fuel tubes entered the engine through the outer wall and each supplied a single-spray nozzle. Fuel flow was controlled by a valve downstream of the heat exchanger (fig. 1), and fuel lines from the valve to the engine were thermally insulated. The six fuel injectors could be positioned radially between the inner diffuser wall and the engine outer wall. All the injectors sprayed upstream.

Two sets of fixed-area, hollow-cone, fuel nozzles were employed to cover the fuel-air ratio range of 0.045 to 0.01. The first set of nozzles was rated at 30.0 gallons per hour at a differential pressure of 100 pounds per square inch; the second set was rated at 17.5 gallons per hour for the same pressure differential. The same nozzles were employed for both preheated-fuel injection and cold-fuel injection.

Flame holders. - The flame holder used in this investigation is shown in figure 3 and consisted of six radial V-gutters with a total over-all blocked area of 37 percent. The open ends of the V-gutters measured $1\frac{1}{2}$ inches across.

Control sleeves. - For some phases of this investigation fuel-mixing control sleeves were inserted into the fuel preparation zone (fig. 1). The sleeves extended from the fuel injectors to the flame holders and were supported by radial struts. Two fuel-mixing control sleeves were employed. The first of these, a $14\frac{1}{2}$-inch-diameter sleeve, was designed to capture three quarters of the total engine-air mass flow. The fuel injectors were located at the center of the diffuser annulus. The second fuel-mixing control sleeve consisted of six individual $3\frac{3}{4}$-inch-diameter sleeves extending from each of the six fuel injectors to the flame holders (fig. 4). With a uniform velocity across the duct assumed, approximately one third of the total engine-air mass flow entered the six control sleeves. Fuel injectors were positioned on the center line of each control sleeve. 2713

Fuel-air sampling. - Vapor and liquid fuel samples were taken on the radial center line of one of the fuel injectors. The sampling probe was made of 1/8-inch Inconel tubing with a 0.018-inch wall and was tapered to a knife-edge orifice at the inlet facing directly into the fuel-air stream. Complete radial traverse across the diffuser annulus was possible at both probe positions.

The collection efficiency of the sampling probe varied between 85 and 90 percent. This efficiency was established in a separate investigation in which water was sprayed into a saturated air stream and the collected sample compared with the known quantity injected.

The sample was ducted from the probes to preheater coils which consisted of 1/4-inch copper tubing wrapped around the engine. Valves permitted the selection of either sampling probe for the common analyzer system (fig. 5).

A diaphragm-type pump evacuated the sample from the engine through the probe. The fuel-air ratio was determined by an NACA fuel-air analyzer (reference 7) which withdrew continuous samples from the discharge line of the diaphragm pump.

METHOD AND PROCEDURE

Operating conditions. - The ram-jet combustor was operated over the following range of inlet conditions:

Inlet-air static pressures, in. Hg abs	32 to 36
Inlet-air temperatures, °F	600
Inlet-air velocities, ft/sec	220 to 260

These values correspond to the combustor-inlet conditions in a ram-jet engine flying at a Mach number of 2.9 at an approximate altitude of 67,000 feet, with a diffuser pressure recovery of 70 percent.

Combustion efficiency. - Combustion-efficiency data were limited to a fuel-air ratio range of 0.017 to 0.045. This range of operation was imposed by calorimeter operating limits and does not represent limits of combustor operation. Combustion temperatures were determined by a heat-balance system similar to the method outlined in reference 8. At a given engine operating condition, the quench-water flow was adjusted to a value insuring complete vaporization of the water. The water mass flow was varied so that outlet temperatures of 600° to 900° F were maintained at the thermocouple station. The total enthalpy change of the fuel, air, quench water, and engine cooling water was divided by the heating value of the fuel to obtain combustion efficiency.

Sampling principles. - Two different techniques of withdrawing the samples were utilized, the spill over and the nonspill over. With the spill-over technique, the sample was obtained at a velocity lower than stream velocity. Most of the intercepted air stream was allowed to spill around the probe while the fuel droplets entered the probe because of the droplet momentum. In the nonspill-over technique, sampling was accomplished at stream velocity. Both techniques have been utilized by other investigators (references 5 and 9); however, for this investigation, corrections were applied to the spill-over calculations to account for fuel vapor drawn into the sampling probe along with the liquid drops.

The correction which was applied to the data obtained by the spill-over sampling technique is described in the appendix.

Fuel-air sampling. - While the total fuel-air ratio sample was obtained, the fuel-air mixture flowed from the sampling probe to the heater, to the diaphragm pump, and, finally, to the NACA analyzer. For the liquid fuel-air sample, the fuel-air mixture entered the probe, flowed to the heater, and was then diluted with a measured quantity of air. This air was metered by a critical flow orifice and was added in sufficient quantity to reduce the fuel-air ratio of the sample to a value within the range of the analyzer. The sample and diluent air mixture was

then, in turn, metered by a critical flow orifice. This latter orifice provided the restriction in the sample line which caused most of the intercepted gas to spill around the probe. From the orifice, the diluted sample flowed to the diaphragm pump which discharged to the analyzer.

The amounts of liquid fuel present at various points across the combustor inlet were evaluated by analyzing samples taken downstream of the fuel injectors. Suitable integration of the liquid-fuel distribution curves obtained from each traverse made possible the determination of the total liquid flows at each sampling station. The degrees of vaporization were then obtained by comparing these liquid fuel flows with the measured quantities of injected fuel.

With combustor conditions held constant at a fuel-air ratio of approximately 0.035, fuel-air surveys were made across the diffuser annulus at two sampling stations located between the point of fuel injection and the flame holder. The sampling stations were located $5\frac{5}{8}$ and $12\frac{1}{8}$ inches downstream of the fuel injectors. Both total fuel-air ratios and liquid fuel-air ratios were determined. These surveys were made with nonpreheated fuel injection as well as with heated fuel injection.

RESULTS

The combustion efficiencies presented in figure 6 were obtained over a range of fuel-air ratios with the fuel injectors located $17\frac{1}{8}$, $10\frac{5}{8}$, and $4\frac{1}{8}$ inches upstream of the flame holders, respectively. The results of varying radial fuel-injector location, fuel temperature at the injectors, and fuel type are also presented in these figures.

In figure 7, the effect of longitudinal injector location upon combustion efficiency is presented. A comparison is made of the combustion efficiency between $4\frac{1}{8}$-, $10\frac{5}{8}$-, and $17\frac{1}{8}$-inch injector locations for the JP-4 fuel injected at the midposition for each station and without preheating. This figure is a cross plot of the data of figure 6.

The effects of controlled fuel-air distribution upon the combustion efficiency of the engine are indicated in figures 8 and 9. Figure 8 presents combustion efficiencies obtained over a range of fuel-air ratios with a $14\frac{1}{2}$-inch-diameter control sleeve. Also in figure 8 is shown the effect of fuel type and fuel temperature upon combustion efficiency. Similar data obtained with six $3\frac{3}{4}$-inch-diameter control sleeves are shown in figure 9.

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The fuel-air ratio profiles at two sampling stations $5\frac{5}{8}$ and $12\frac{1}{8}$ inches downstream of a fuel nozzle are presented in figure 10 for JP-4 fuel. Similar data are shown in figure 11 for 62-octane gasoline and the $12\frac{1}{8}$-inch sampling station. The curves show total and liquid fuel-air ratios obtained with and without fuel preheating.

DISCUSSION

Fuel vaporization studies. - An indication of the rate of vaporization of a fuel spray was obtained from the results of the total and liquid fuel-air ratio distribution studies presented in figures 10 and 11. These distributions were determined in one circumferential plane only and, as shown, were asymmetrical about the nozzle axis located halfway between the outer and inner wall. From the ratio of the integrated value of the liquid fuel-air ratio curves to the over-all fuel-air ratio, the following percentages of evaporated fuel were obtained:

Distance downstream from fuel injector (in.)	Fuel	Percentage vaporized at given fuel temperature	
		410° F	90° F
$5\frac{5}{8}$	JP-4	81	58
$12\frac{1}{8}$	JP-4	92	78
$12\frac{1}{8}$	Gasoline	--	80

Fuel state. - The effect of fuel preheating on combustion efficiency was found to be negligible, as is shown in figures 6, 8, and 9, and table II. The combustion efficiencies obtained with fuel preheated to a temperature sufficient for complete flash vaporization showed little gains over nonpreheated fuel injection. The fuel vaporization studies show that 58 percent of the fuel was vaporized even under the most adverse conditions investigated, that is, with a short ($5\frac{5}{8}$ inch) distance available for vaporization and with cold (90° F) fuel. These data therefore indicate that the portion of the fuel in vapor state is adequate to provide the initial vapor-fuel and air mixtures necessary for efficient combustion at all conditions investigated. Thus the addition of sufficient

heat to the fuel to vaporize the residual fuel left unvaporized by the air stream resulted in no important increase in combustion efficiency. It should be noted that in an engine operating at the same inlet-air temperature but at lower pressures the fuel vaporization rate would be still greater than observed here.

Fuel-injection location. - The combustion-efficiency data obtained with the fuel injectors located $17\frac{1}{8}$, $10\frac{5}{8}$, and $4\frac{1}{8}$ inches upstream of the flame holder show that mixing length had little effect. Peak combustion efficiencies varied from 92 to 95 percent as is seen in figures 6 and 7, respectively. The absence of any significant effect of mixing length on combustion efficiency seems reasonable since a large portion of the fuel was vaporized even with the shortest mixing length and with cold-fuel injection. 2713

The data presented in figure 6, however, demonstrated that the radial position of the fuel injection was of some importance. A variation in combustion efficiency of approximately 5 percent was found between injection near the diffuser wall and injection near the outer wall.

Fuel type. - Fuel type was found to have a slight effect on combustion efficiency. An increase of approximately 2 percent was realized with gasoline over JP-4 at the fuel-injector location nearest to the flame holder as shown in figure 6(g). For the fuel-injector location farthest upstream of the flame holders, the increase was 3 to 5 percent, as shown in figures 6(a) and 6(b). Although these increases were slight, and of the same order as the experimental accuracy, the trends were always in the same direction. These trends in efficiency cannot be explained from the results of the vaporization studies since it is seen that at a mixing length of $12\frac{1}{8}$ inches the percent of fuel vaporized was 78 for JP-4 and 80 for 62-octane gasoline.

Fuel-air mixing control. - A possible explanation for the increase in combustion efficiency with 62-octane fuel over and above JP-4 is the change in fuel-spray penetration with the fuel type. This fact is borne out by comparing figure 8 with figures 6(a) and 6(b). In obtaining the data for figure 8, a $14\frac{1}{2}$-inch-diameter control sleeve was employed to limit the extent of fuel penetration into the air stream. With the fuel penetration physically limited by the control sleeve, the two fuels resolve to similar combustion efficiencies, indicating that proper control of the fuel distribution is more critical in the fuel preparation zone than fuel type.

With the individual sleeves for fuel-mixing control, combustion efficiency was maintained between 95 and 92 percent over a fuel-air ratio range from 0.0475 to 0.0175, as shown in figure 9. These control sleeves prevented the fuel from spreading both radially and circumferentially, and provided high combustion efficiency through a wider range of fuel-air ratios than any of the configurations investigated.

SUMMARY OF RESULTS

The following results were obtained from a 16-inch ram-jet engine operating at an inlet pressure of approximately 1 atmosphere and an inlet temperature of 600° F corresponding to a flight Mach number of 2.9 with a diffuser recovery factor of 70 percent:

1. Variation in the longitudinal location of the fuel injectors had little effect on the combustion efficiency.

2. Preheating the primary fuel to its flash vaporizing temperature resulted in no gain in combustion efficiency for either the MIL-F-5624A grade JP-4 fuel or the 62-octane gasoline.

3. Fuel-air ratio surveys indicated that for a fuel temperature of 100° F at the injector, 58 percent of the fuel was vaporized within 6 inches of the point of injection.

4. The use of six, individual, fuel control sleeves resulted in an almost constant combustion efficiency of approximately 93 percent over a fuel-air ratio range of 0.0475 to 0.0175.

5. Without fuel distribution control, an increase of 2 to 5 percent in the combustion efficiency was realized with 62-octane gasoline fuel as compared with JP-4 fuel. With controlled fuel distribution, no gain in combustion efficiency was realized with 62-octane gasoline.

6. Varying the radial position of the fuel injectors resulted in combustion-efficiency variations of approximately 5 percent.

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APPENDIX - CORRECTION OF DATA OBTAINED WITH SPILL-OVER SAMPLING TECHNIQUE

In employing the spill-over technique, with a conductivity-type mixture analyzer, a correction is required to account for the fuel vapor that is captured along with the liquid fuel sample. The following analysis was utilized to obtain this correction for measurements made with the spill-over technique, and the following symbols were used: 2713

f_l liquid fuel-air ratio in main stream at point of sampling

f_p fuel-air ratio of spill-over sample after addition of diluent air

f_t total fuel-air ratio in main stream at point of sampling

f_v vapor fuel-air ratio in main stream at point of sampling

W_a weight flow of air intercepted by probe, lb/hr

W_a' weight flow of air captured by probe, lb/hr

W_d weight flow of diluent air added to spill-over sample, lb/hr

W_f weight flow of fuel captured by probe, lb/hr

W_l weight flow of liquid fuel captured by probe, lb/hr

W_p total weight flow through sampling lines after addition of diluent air, lb/hr

This analysis was based on two assumptions: (1) All the intercepted liquid fuel droplets enter the probe because of their higher momentum, and (2) the weight flow of air per unit area is constant throughout the combustor. Assumption (1) is the basis of the spill-over sampling technique and has been shown to be substantially correct.

The droplet collection efficiency of the sampling probe employed in this investigation was experimentally determined and found to be approximately 90 percent. Assumption (2) has also been found to be valid. Traverses taken across the annulus of the engine showed flat velocity distributions. Therefore,

$$f_l = \frac{W_l}{W_a} \tag{1}$$

by definition, where W_l is all the fuel captured minus the fuel vapor captured from the free stream by the probe.

Therefore,

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$$W_l = W_f - W_a' f_v \tag{2}$$

or

$$W_l = W_p \frac{f_p}{1 + f_p} - f_v \left(W_p - W_d - W_p \frac{f_p}{1 + f_p}\right) \tag{3}$$

Thus,

$$f_l = \frac{W_p \dfrac{f_p}{1 + f_p} - (f_t - f_l)\left(W_p - W_d - W_p \dfrac{f_p}{1 + f_p}\right)}{W_a} \tag{4}$$

Rearranging and simplifying the above expression result in

$$f_l = \frac{W_d f_t (1 + f_p) - W_p\,(f_t - f_p)}{(W_a + W_d)(1 + f_p) - W_p} \tag{5}$$

All the quantities of equation (5) were measured with the exception of W_a. This quantity was determined from the known cross-sectional area of the probe opening and the known weight flow of air per unit area in the combustor. Values of the total fuel-air ratio were determined from traverses which were made with the nonspill-over technique.

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TABLE I - SPECIFICATIONS AND ANALYSIS OF PRIMARY ENGINE FUEL

MIL-F-5624A GRADE JP-4 AND 62-OCTANE GASOLINE

	Specifications JP-4	Analysis	
		JP-4	62 Octane
A.S.T.M. distillation D86-46 (°F)			
Initial boiling point		140	110
Percentage evaporated			
5		199	137
10		224	154
20		250	178
30		270	200
40		290	218
50		305	235
60		325	250
70		352	265
80	-	384	284
90	250 (max)	427	305
Final boiling point	550 (max)	487	358
Residue (percent)	1.5 (max)	1.2	1.3
Loss (percent)	1.5 (max)	0	1.4
Aromatics (percent by volume) A.S.T.M. D875-46T	25 (max)		
Specific gravity °A.P.I.	40 (min), 58 (max)	0.765	0.716
Reid vapor pressure (lb/sq in.)	2.0 (min), 3.0 (max)	2.7	6.7
Hydrogen-carbon ratio		0.169	0.182
Net heat of combustion (Btu/lb)	18,400 (min)	18,700	18,925

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TABLE II - COMPILATION OF PERFORMANCE DATA

[Inlet-air temperature, 600° F; engine mass flow, 14.4 lb/sec]

Combustor configuration	Fuel	Combustion efficiency (percent)	Fuel temperature (°F)	Fuel pressure (lb/sq in. gage)	Inlet velocity (ft/sec)	Fuel-air ratio	Inlet pressure (in. Hg abs)
Fuel injectors at midposition of annulus and $17\frac{1}{8}$ in. upstream of flame holders; no control sleeve	JP-4	93	93	280	230	0.0399	35.2
	JP-4	94	93	240	233	.0364	34.9
	JP-4	90	93	200	236	.0331	34.5
	JP-4	92	93	150	241	.0285	33.8
	JP-4	86	97	90	249	.0231	32.8
	JP-4	78	97	70	253	.0201	32.2
	JP-4	94	415	380	230	.0397	35.2
	JP-4	94	282	280	232	.0373	35.0
	JP-4	92	100	350	226	.0448	36.0
	62 Octane	94	94	340	229	.0423	35.5
	62 Octane	98	94	260	232	.0354	34.9
	62 Octane	87	94	200	235	.0318	34.4
	62 Octane	95	94	160	240	.0278	33.8
	62 Octane	89	96	100	246	.0221	32.9
	62 Octane	85	98	80	250	.0196	32.4
	62 Octane	99	280	300	233	.0350	34.7
Same as above, except fuel injectors are 1 in. toward inner wall from midposition	JP-4	93	97	250	235	0.0382	34.6
	JP-4	95	411	370	233	.0391	34.9
	JP-4	95	280	280	233	.0376	34.8
	JP-4	95	100	200	237	.0331	34.3
	JP-4	93	100	150	241	.0288	33.7
	JP-4	86	100	70	252	.0200	32.3
Fuel injectors 1 in. toward outer wall from midposition of annulus and injectors $17\frac{1}{8}$ in. upstream of flame holders; no control sleeve	JP-4	92	420	350	235	0.0376	34.2
	JP-4	91	454	330	236	.0336	34.0
	JP-4	91	380	145	250	.0217	32.2
	JP-4	89	100	320	231	.0425	34.8
	JP-4	91	100	240	235	.0365	34.2
	JP-4	90	100	190	238	.0322	33.8
	JP-4	88	100	145	242	.0279	33.2
	JP-4	83	100	95	247	.0228	32.5
	62 Octane	95	280	320	234	.0361	34.4
	62 Octane	96	110	280	235	.0365	34.6
	62 Octane	95	110	210	239	.0315	33.9
	62 Octane	93	110	150	243	.0271	33.3
	62 Octane	89	110	100	253	.0219	32.6
Fuel injectors 1 in. out radially from midposition and injectors $10\frac{5}{8}$ in. upstream of flame holder; no control sleeve	JP-4	89	90	370	230	0.0472	34.8
	JP-4	94	88	310	230	.0434	34.5
	JP-4	88	88	250	231	.0376	34.1
	JP-4	87	89	200	234	.0236	33.7
	JP-4	85	90	130	240	.0272	32.9
	JP-4	87	91	100	242	.0240	32.6
	JP-4	83	92	55	264	.0189	32.0
	JP-4	74	94	25	252	.0148	31.3
	JP-4	92	400	380	228	.0397	34.6
	JP-4	90	272	285	232	.0381	34.1
Same as above, except fuel injectors in midposition	62 Octane	93	92	350	226	0.0420	35.1
	62 Octane	94	91	300	230	.0368	34.5
	62 Octane	96	92	195	234	.0293	33.8
	62 Octane	92	92	120	241	.0228	32.8
	62 Octane	87	94	55	249	.0164	31.8
	JP-4	87	91	190	234	.0338	33.8
	JP-4	90	91	130	238	.0282	33.3
	JP-4	88	93	75	245	.0216	32.4
	JP-4	80	95	45	252	.0188	31.7
	JP-4	95	400	355	230	.0398	34.7
	JP-4	95	269	265	232	.0377	34.5

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TABLE II - COMPILATION OF PERFORMANCE DATA - Concluded

[Inlet-air temperature, 600° F; engine mass flow, 14.4 lb/sec]

Combustor configuration	Fuel	Combustion efficiency (percent)	Fuel temperature (°F)	Fuel pressure (lb/sq in. gage)	Inlet velocity (ft/sec)	Fuel-air ratio	Inlet pressure (in. Hg abs)
Fuel injectors, 1 in. inward from midposition; same injector-to-flame-holder distance	JP-4	92	89	315	227	0.0454	34.7
	JP-4	98	89	250	228	.0385	34.3
	JP-4	95	90	170	236	.0309	33.6
	JP-4	90	91	85	244	.0227	32.5
	JP-4	88	93	45	250	.0165	31.8
	JP-4	99	403	370	231	.0396	34.4
	JP-4	98	270	280	233	.0378	34.1
Fuel injectors at midposition of annulus and $4\frac{1}{8}$ in. upstream of flame holder; no control sleeve	JP-4	89	90	250	226	0.0500	35.5
	JP-4	89	370	320	224	.0500	35.5
	JP-4	92	100	180	228	.0436	34.9
	JP-4	91	260	225	228	.0457	35.0
	JP-4	94	100	150	232	.0382	34.4
	JP-4	92	100	120	235	.0339	34.1
	JP-4	85	290	150	233	.0366	34.3
	JP-4	91	100	70	240	.0268	33.3
	JP-4	86	100	30	247	.0196	32.3
	62 Octane	93	90	220	230	.0435	34.7
	62 Octane	92	380	340	228	.0446	35.0
	62 Octane	97	100	150	233	.0372	34.3
	62 Octane	95	285	170	234	.0345	34.2
	62 Octane	92	100	50	244	.0231	32.8
Fuel injectors same as above, except 1 in. toward inner wall from midposition	62 Octane	84	90	250	231	0.0495	34.5
	62 Octane	92	385	350	231	.0424	34.6
	62 Octane	76	100	150	234	.0365	33.9
	62 Octane	96	280	170	236	.0344	33.8
	62 Octane	95	100	70	240	.0264	33.1
	62 Octane	97	100	30	245	.0199	32.4
Fuel injectors at midposition of control-sleeve annulus and $17\frac{1}{8}$ in. upstream of flame holder; $14\frac{1}{2}$-in.-diam. control sleeve	JP-4	96	80	310	231	0.0423	35.4
	JP-4	98	80	290	231	.0402	35.4
	JP-4	98	80	250	233	.0378	35.0
	JP-4	98	80	200	236	.0342	34.6
	JP-4	98	80	150	241	.0289	33.9
	JP-4	96	80	125	243	.0268	33.5
	JP-4	94	80	100	246	.0235	33.0
	JP-4	89	80	75	248	.0208	32.7
	JP-4	81	80	50	254	.0177	32.0
	JP-4	98	394	370	231	.0398	35.3
	JP-4	98	430	330	234	.0357	34.7
	JP-4	99	290	225	241	.0336	33.9
	62 Octane	99	80	270	234	.0367	35.0
	62 Octane	97	80	190	238	.0309	34.4
	62 Octane	98	80	150	243	.0265	33.7
	62 Octane	93	80	100	247	.0225	33.1
Fuel injectors at center lines of sleeves and $17\frac{1}{8}$ in. upstream of flame holder; six individual control sleeves	JP-4	95	94	350	229	0.0469	34.8
	JP-4	98	94	290	229	.0431	34.8
	JP-4	95	94	230	235	.0375	34.1
	JP-4	92	94	185	238	.0334	33.7
	JP-4	96	98	130	242	.0286	33.2
	JP-4	92	98	85	247	.0230	32.5
	JP-4	92	106	50	251	.0181	31.8
	JP-4	76	106	25	256	.0145	31.2
	JP-4	95	410	390	229	.0431	34.8
	JP-4	91	420	370	231	.0393	34.5
	JP-4	94	320	220	236	.0330	33.7
	JP-4	92	340	180	240	.0288	33.2

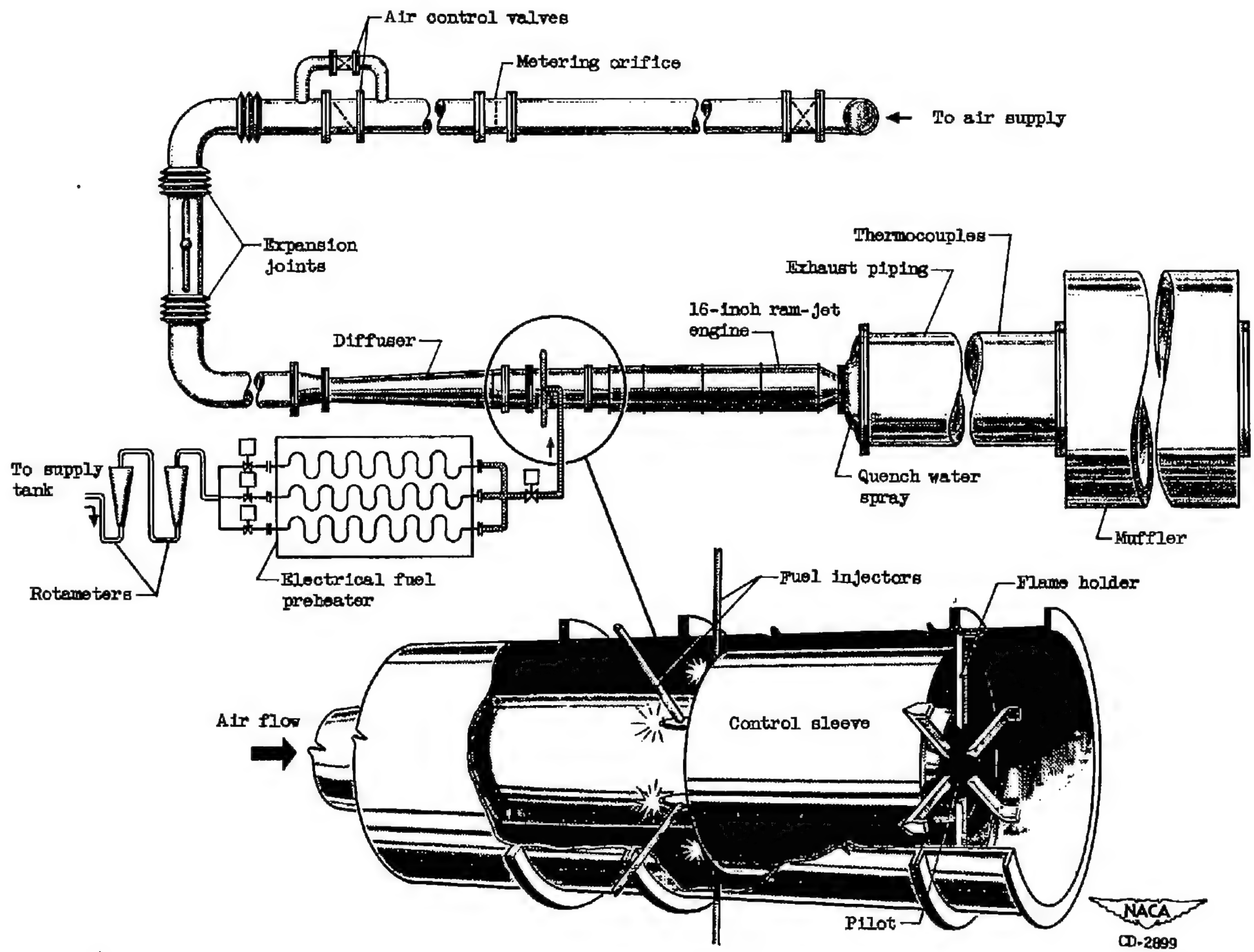

Figure 1. - Installation of 16-inch ram-jet engine.

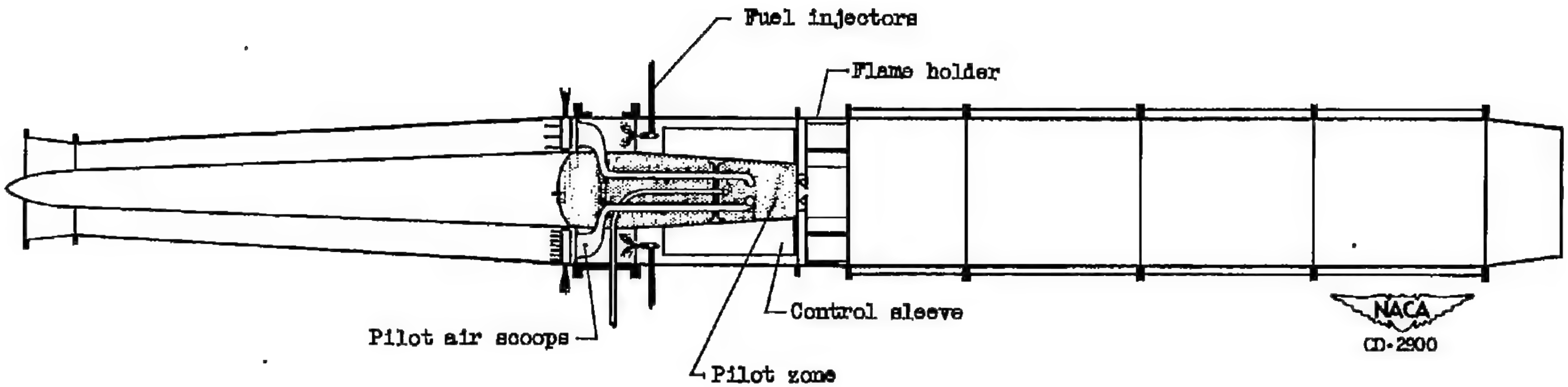

Figure 2. - Sketch of 16-inch ram-jet engine showing position of fuel injectors, flame holder, and mixing control sleeve.

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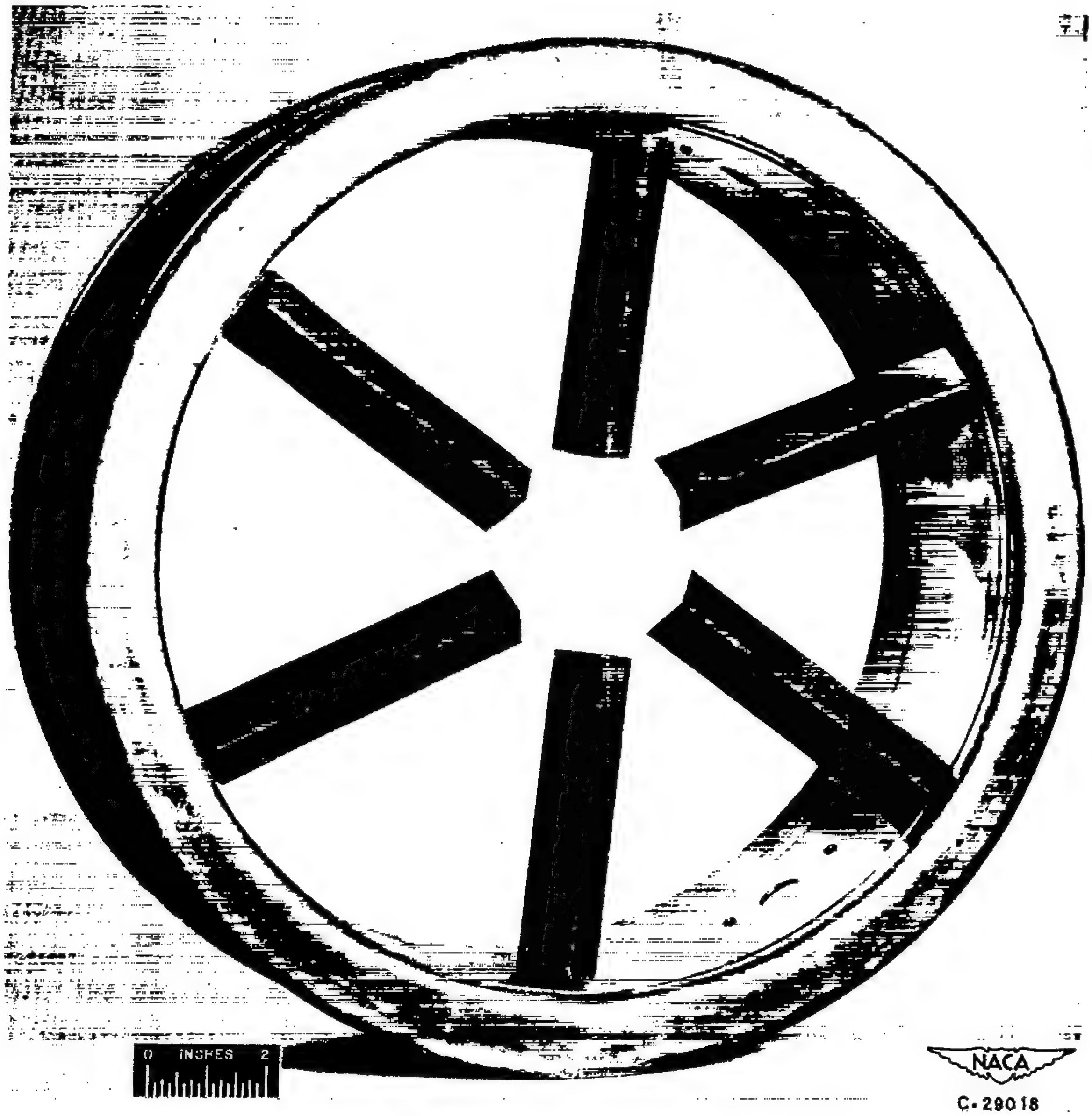

Figure 3. - Flame-holder configuration showing radial V-gutter, upstream face.

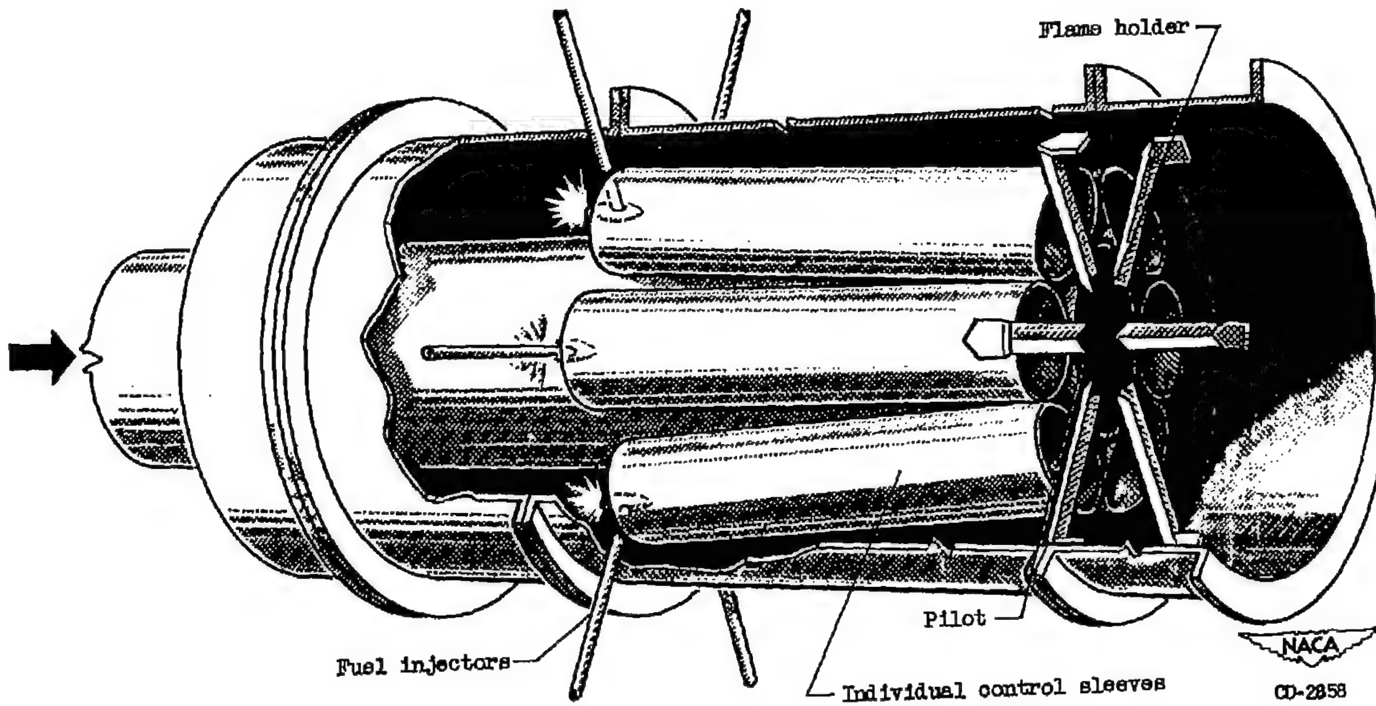

Figure 4. - Installation of six individual fuel-mixing control sleeves between fuel injectors and flame holder.

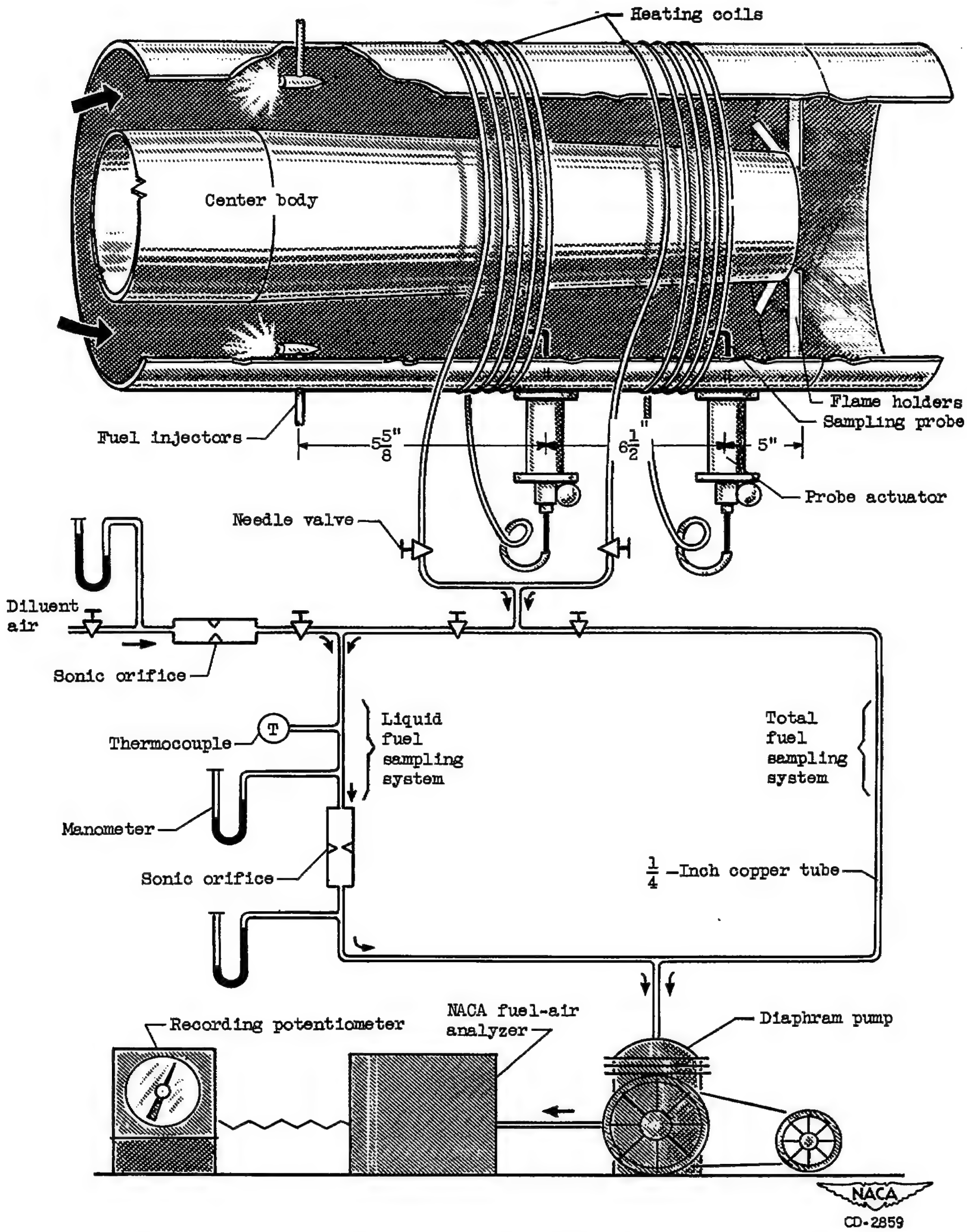

Figure 5. - Sketch of total fuel-air and liquid fuel-air sampling system.

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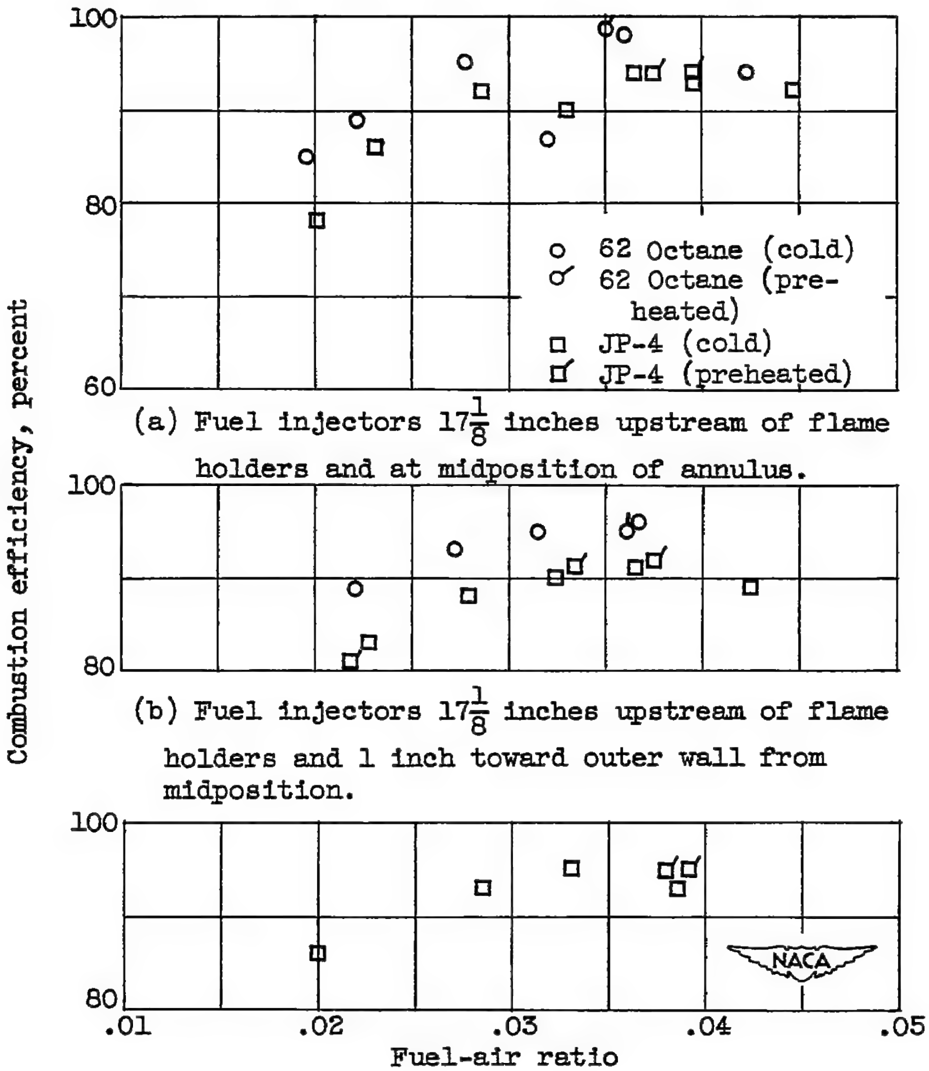

(a) Fuel injectors $17\frac{1}{8}$ inches upstream of flame holders and at midposition of annulus.

(b) Fuel injectors $17\frac{1}{8}$ inches upstream of flame holders and 1 inch toward outer wall from midposition.

(c) Fuel injectors $17\frac{1}{8}$ inches upstream of flame holders and 1 inch toward inner wall from midposition.

Figure 6. - Effect of fuel type, fuel temperature, and fuel-injector radial position on combustion efficiency. Fuel, MIL-F-5624A grade JP-4 and 62-octane gasoline.

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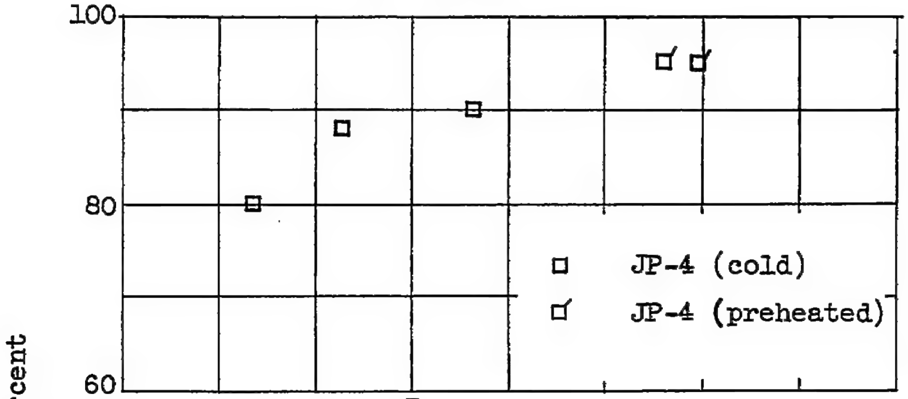
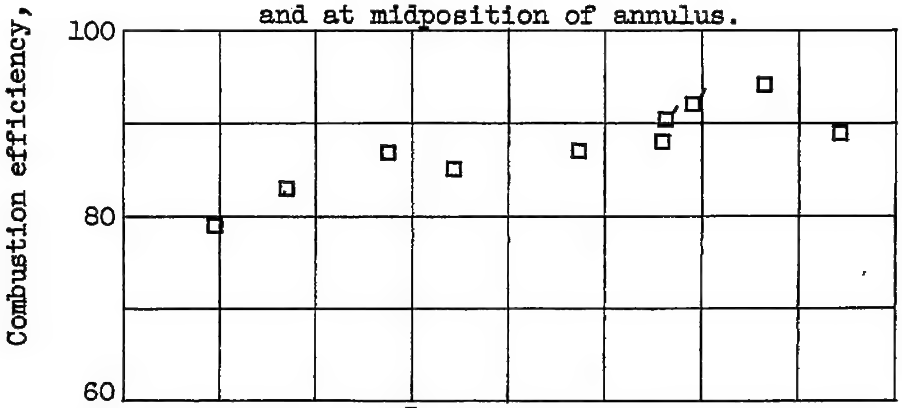
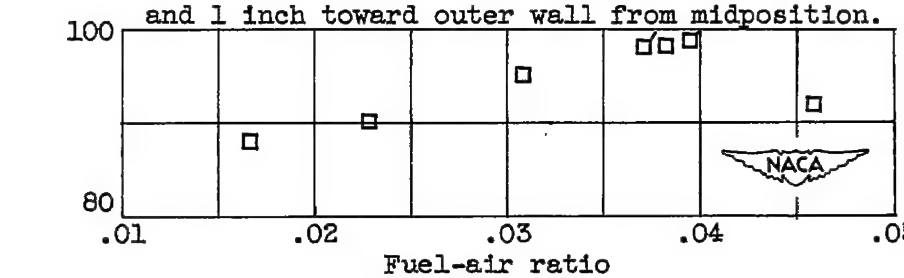


(d) Fuel injectors $10\frac{5}{8}$ inches upstream of flame holder and at midposition of annulus.



(e) Fuel injectors $10\frac{5}{8}$ inches upstream of flame holder and 1 inch toward outer wall from midposition.



(f) Fuel injectors $10\frac{5}{8}$ inches upstream of flame holder and 1 inch toward inner wall from midposition.

Figure 6. - Continued. Effect of fuel type, fuel temperature, and fuel-injector radial position on combustion efficiency. Fuel, MIL-F-5624A grade JP-4 and 62-octane gasoline.

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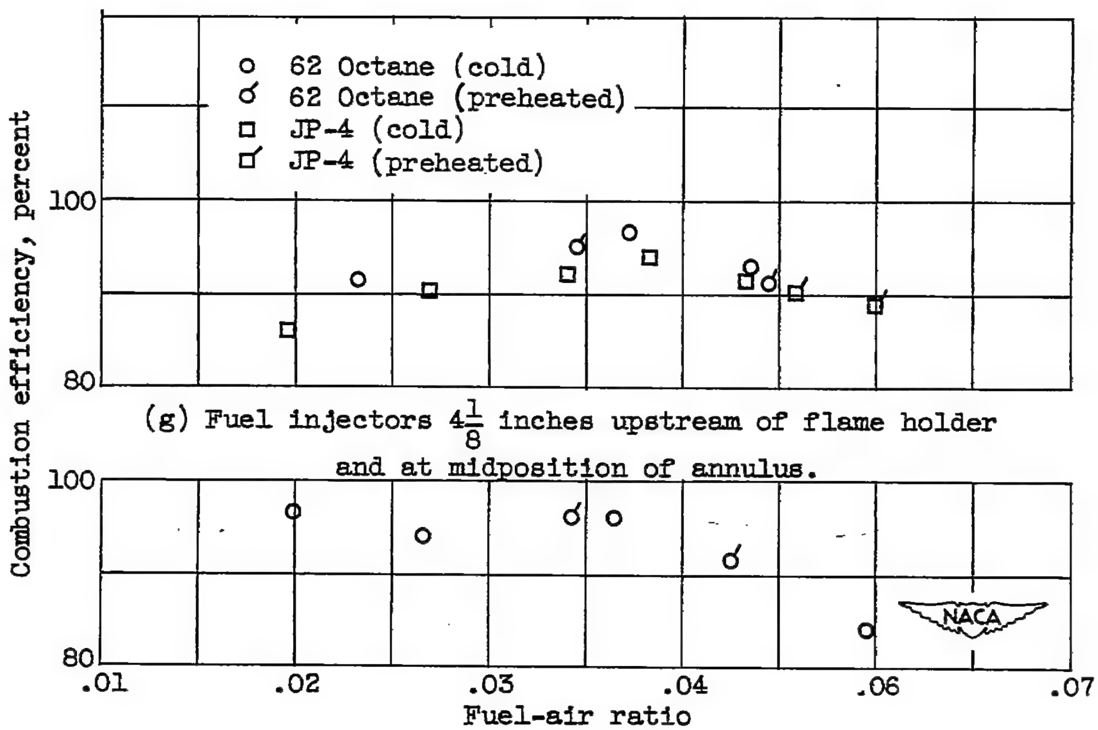


(g) Fuel injectors $4\frac{1}{8}$ inches upstream of flame holder and at midposition of annulus.

(h) Fuel injectors $4\frac{1}{8}$ inches upstream of flame holder and 1 inch toward inner wall from midposition.

Figure 6. - Concluded. Effect of fuel type, fuel temperature, and fuel-injector radial position on combustion efficiency. Fuel, MIL-F-5624A grade JP-4 and 62-octane gasoline.

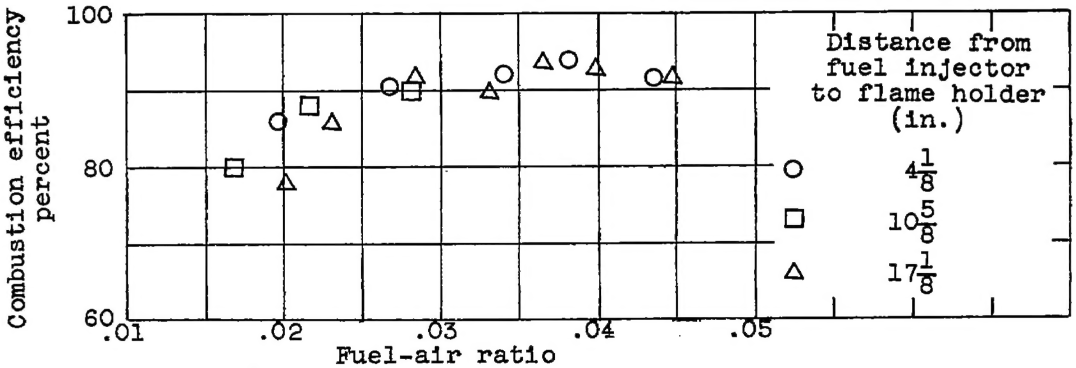


Figure 7. - Comparison of combustion efficiencies for three injector distances upstream of the flame holders for cold MIL-F-5624A grade JP-4 fuel and fuel injectors at midposition of annulus.

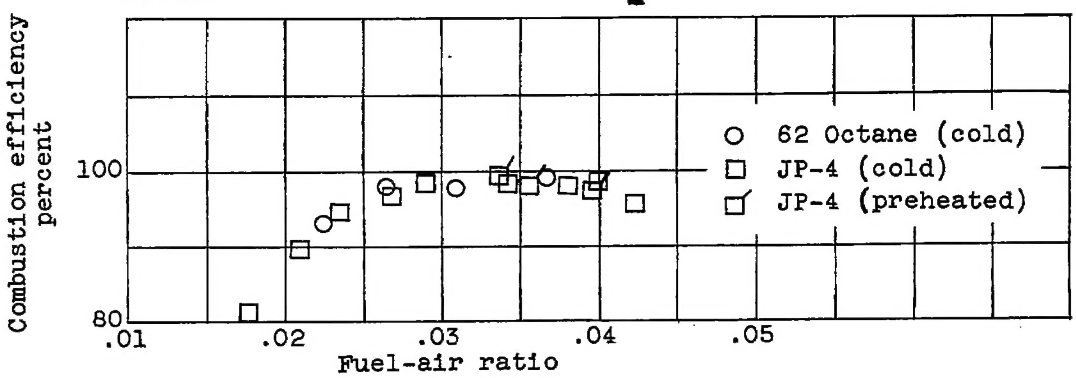


Figure 8. - Effect of fuel type and fuel temperature on combustion efficiency with a $14\frac{1}{2}$-inch-diameter fuel-mixing control sleeve and fuel injectors $17\frac{1}{8}$ inches upstream of flame holders. Fuel, MIL-F-5624A grade JP-4 and 62-octane gasoline.

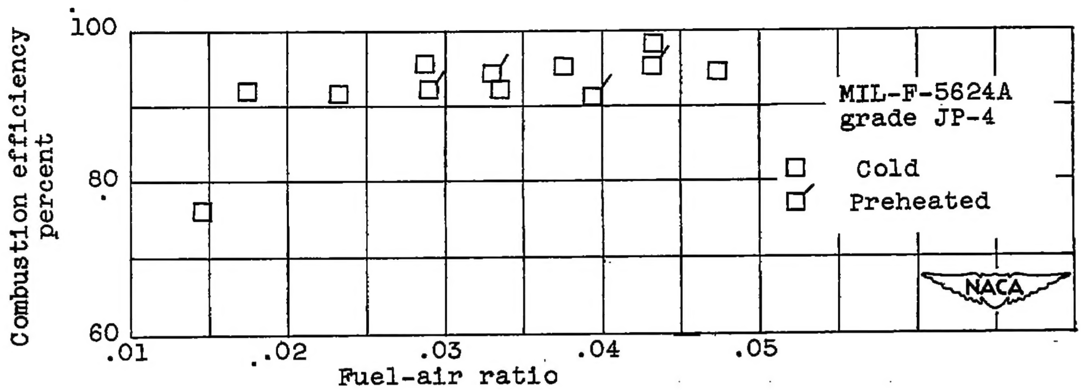
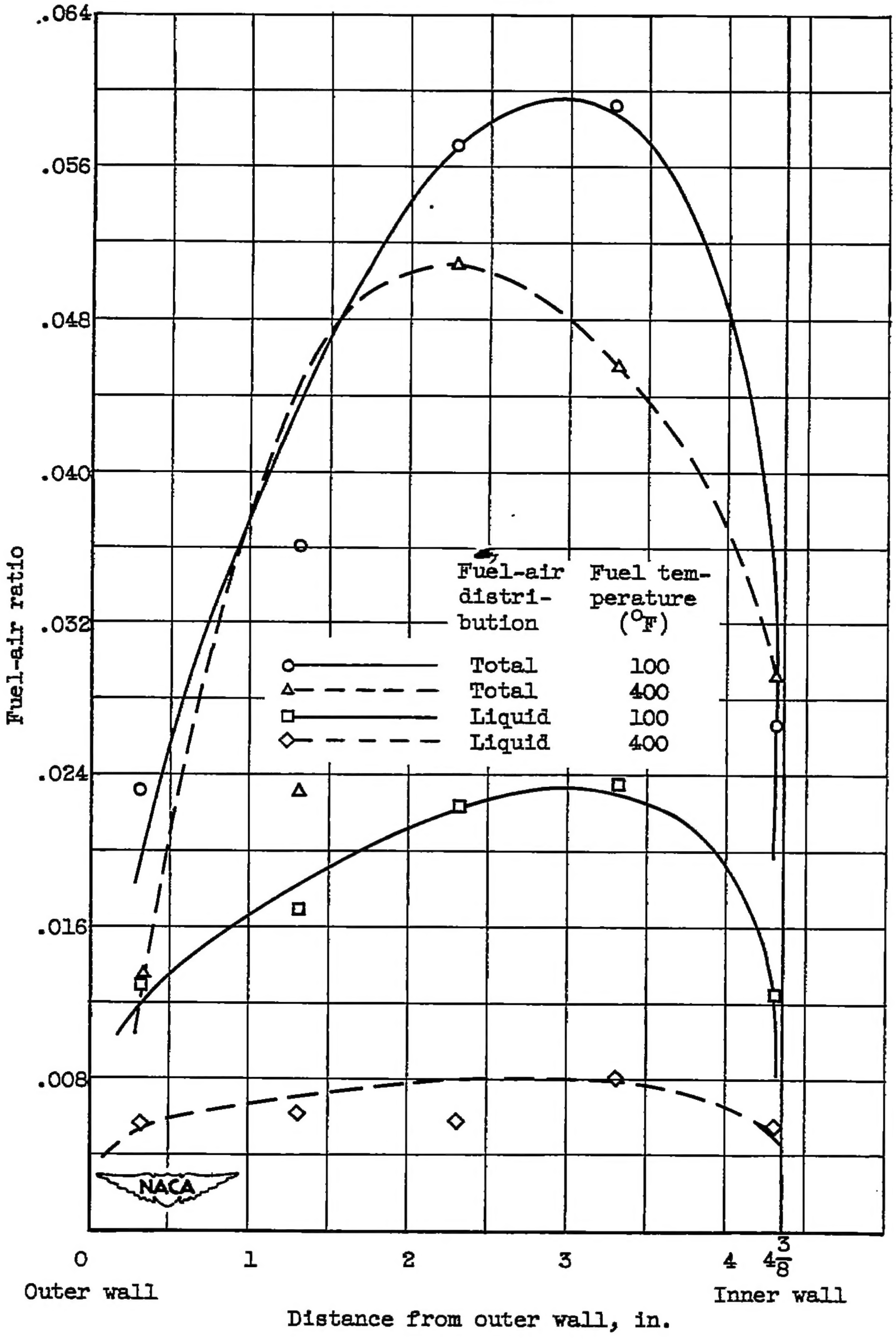
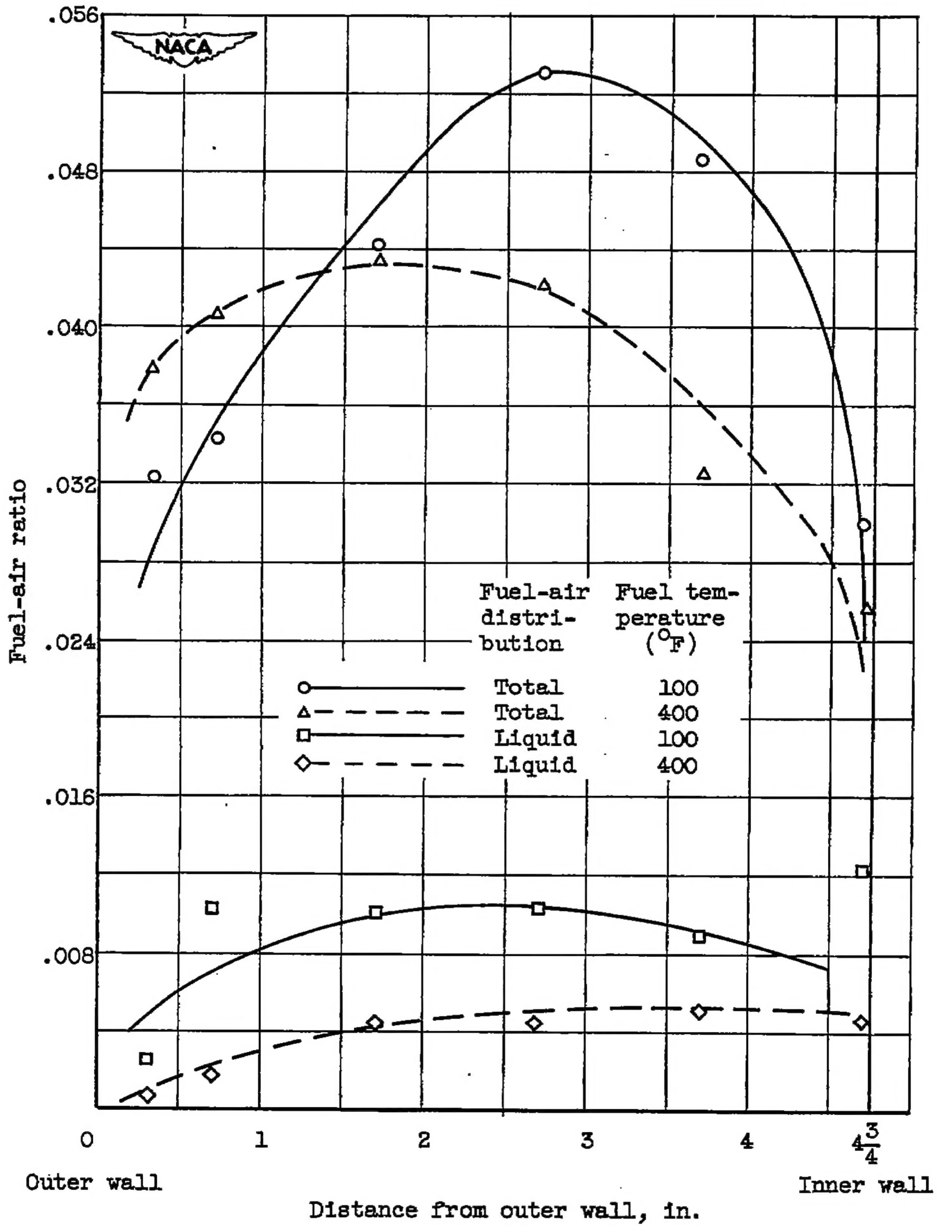


Figure 9. - Effect of fuel temperature on combustion efficiency with six individual fuel-mixing control sleeves and fuel injectors $17\frac{1}{8}$ inches upstream of flame holders.



(a) $5\frac{5}{8}$ Inches downstream of fuel injectors.

Figure 10. - Total and liquid fuel-air distributions for MIL-F-5624A grade JP-4 fuel. Over-all fuel-air ratio, 0.037.



(b) $12\frac{1}{8}$ Inches downstream of fuel injectors.

Figure 10. - Concluded. Total and liquid fuel-air distributions for MIL-F-5624A grade JP-4 fuel. Over-all fuel-air ratio, 0.037.

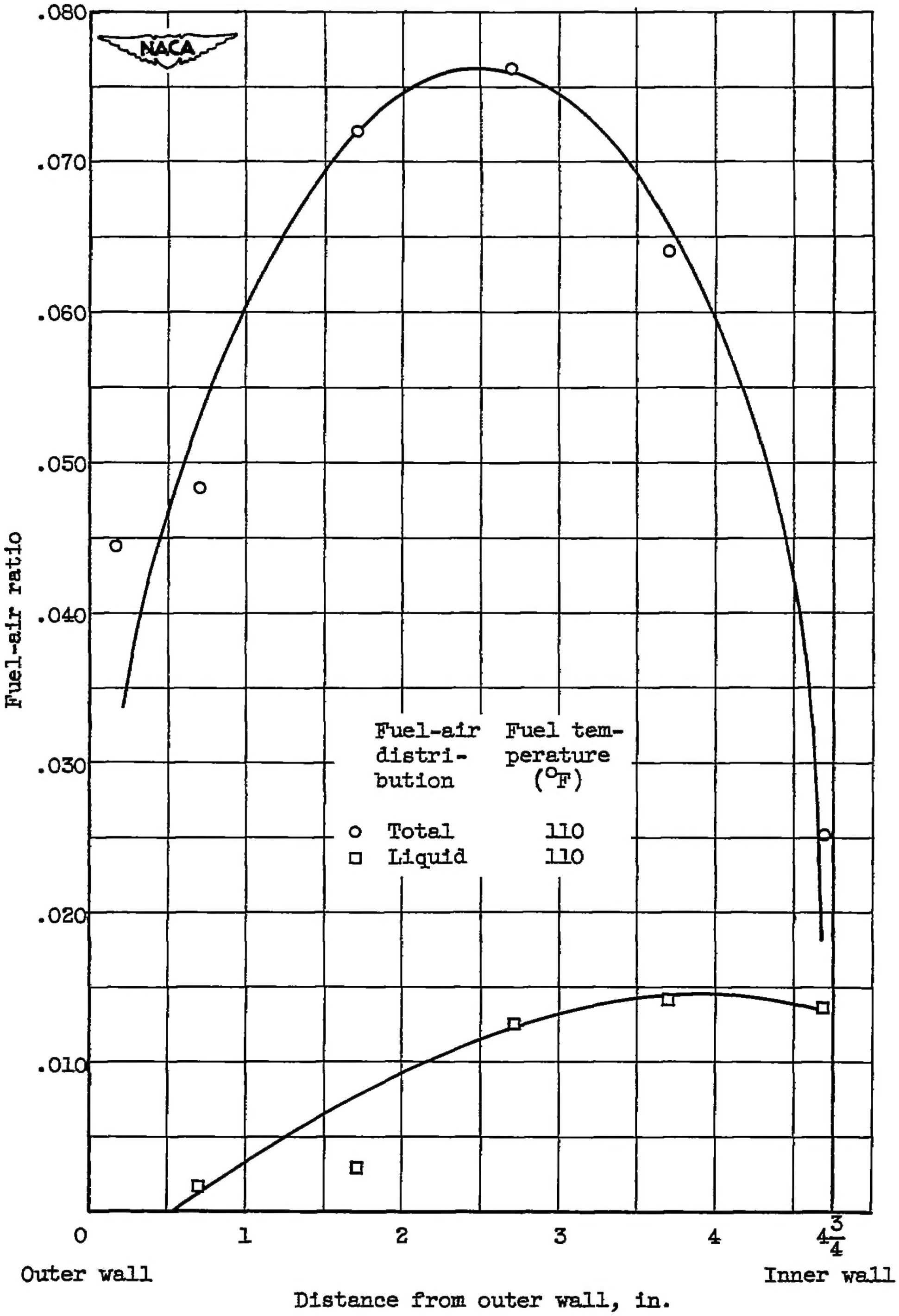


Figure 11. - Total and liquid fuel-air distributions $12\frac{1}{8}$ inches downstream of fuel injectors for 62-octane gasoline. Over-all fuel-air ratio, 0.035.